NACA

RESEARCH MEMORANDUM

RECENT CONTROL STUDIES

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SUMMARY

A brief review of the present status of control research is presented and a few of the more recent control studies are discussed. The results indicate that, in addition to flaps and spoilers, air can now be used in the form of jet controls or reaction controls as alternate means of controlling the aircraft.

INTRODUCTION

It is the purpose of this paper to give a brief review of the overall picture regarding control characteristics and then to discuss in some detail a few of the more recent control studies.

Figure 1 shows the types of controls that are considered and the order in which they are discussed. At the top of the figure are the familiar flap and spoiler types. At the bottom of the figure are the jet control and the so-called reaction control. The jet control obtains most of its effectiveness, as does the spoiler, by changing the circulation around the wing, but in addition it may be supplemented by the reaction of the jets blowing out of the wing. In contrast the reaction control obtains all of its effectiveness by deflecting the jet exhaust stream. It should be noted that although the flap, spoiler, and jet controls are pictured here as lateral controls and the reaction control as a longitudinal control, all of the controls can be designed as either lateral, longitudinal, or directional control devices. In order to complete the picture and include the various controls not mentioned here, a bibliography of control work done by the National Advisory Committee for Aeronautics since 1946 is included.

COEFFICIENTS AND SYMBOLS

A aspect ratio

A_i cross-sectional area of inlet, sq ft

A_j cross-sectional area of jets, sq ft

b wing span, ft

$C_{h_{\delta,\omega}}$ in-phase hinge-moment parameter, $\frac{\text{Real part of } M_\delta}{2M'q}$

$C_{h_{\dot{\delta},\omega}}$ out-of-phase hinge-moment parameter, $\frac{\text{Imaginary part of } M_\delta}{2M'q}$

C_l rolling-moment coefficient, $\frac{\text{Rolling moment}}{qSb}$

C_N normal-force coefficient, $\frac{\text{Normal force}}{qS}$

C_μ momentum coefficient, $\frac{WV_j}{gqS}$

c wing chord, ft

c_b control balance chord ahead of hinge line, ft

c_f control chord behind hinge line, ft

g acceleration due to gravity, ft/sec^2

k_a control-surface reduced frequency, $\frac{\omega(c_f + c_b)}{2V}$

M free-stream Mach number

M' area moment of control area rearward of hinge line, taken about hinge line, ft^3

M_δ aerodynamic hinge moment of control per unit deflection, positive trailing edge down, ft-lb/radian

$pb/2V$ wing-tip helix angle, radians

p rate of roll, radians/sec

q free-stream dynamic pressure, lb/sq ft

S	wing area including area within fuselage, sq ft
S_E	exposed wing area, sq ft
V	free-stream velocity, ft/sec
V_j	jet velocity, ft/sec
W	weight rate of flow, lb/sec
α	angle of attack, deg
δ	control deflection, deg
$\Lambda_{c/4}$	sweepback of quarter-chord line, deg
ω	angular frequency of oscillation, radians/sec

DISCUSSION

General

The characteristics of flap-type controls can be estimated in the subsonic speed range by a combination of theoretical and empirical methods. In the transonic speed range empirical correlations and/or specific tests must be relied on almost entirely. At supersonic speeds available theoretical and empirical methods may again be used to predict the characteristics. All of these methods have limitations as to the range of applicability - for example, figure 2 shows the range of angle of attack α and control deflection δ in which the methods apply for flap-type controls at supersonic speeds. Boundaries shown for constant free-stream Mach number represent the values of α and δ below which the available methods will accurately predict the control characteristics. At a Mach number of 3 the range of both α and δ is rather large, but this range decreases as the Mach number is decreased until at $M = 1.25$ the positive range of α and δ has practically disappeared. The scope of this chart is actually expanded by the fact that for symmetrical airfoils the negative angle-of-attack range shown can also be considered as positive angle of attack for negative flap deflections.

The situation is much the same for spoiler-type controls as for flap-type controls except that empirical methods must be used throughout the speed range since separated flow is always associated with spoilers. So little is known about the jet controls and reaction controls at this time that specific tests are generally required when a new configuration is considered.

Flap-Type Controls

Some recent dynamic hinge-moment results obtained at transonic speeds on an unswept wing will be discussed next. Figure 3 shows the variation of the in-phase component of the hinge moment $C_{h_{\delta,\omega}}$ with Mach number M for two controls on an unswept wing at zero angle of attack. The values of $C_{h_{\delta,\omega}}$ are given for a control having a small overhang $\left(\frac{c_b}{c_f} = 0.2\right)$ and a large overhang $\left(\frac{c_b}{c_f} = 1.0\right)$ at a reduced frequency k_a of about 0.10. It can be seen that the variation of the in-phase component of the hinge moment with both M and $\frac{c_b}{c_f}$ is about the same as the variation of the static hinge-moment coefficient. That is, the small overhang is underbalanced throughout the Mach number range, whereas the 100-percent overhang is overbalanced in the Mach number range covered.

Figure 4 presents the damping coefficient or out-of-phase component of hinge moment $C_{h_{\dot{\delta},\omega}}$ plotted against flap deflection for the same controls as shown in figure 3. The parameter $C_{h_{\dot{\delta},\omega}}$ varies with flap deflection at all the Mach numbers shown. Another very significant thing is the pronounced change in damping with overhang. At the lowest subsonic speed $(M = 0.7)$ the 100-percent overhang reduces the damping at all values of δ and, in fact, becomes unstable at large flap deflections. This instability is believed to be associated with the unporting of the balance and the accompanying large changes in flap characteristics. At the higher subsonic Mach number and near the speed of sound a large increase in damping results from the overhang except for very small deflections at $M = 1.01$. This instability may be associated with the effect of the unsteady shock wave on the flap.

Spoiler-Type Controls

Among the advantages cited for the spoiler-type control are good effectiveness throughout the speed range and low wing torsional loads. Figure 5 presents the results of some recent flight tests made by North American Aviation, Inc., with an experimental swept-wing airplane. The variation of rolling effectiveness $pb/2V$ with Mach number M is presented for the airplane equipped with flap-type ailerons and with spoiler-type ailerons (in this case, spoiler-slot-deflectors). Above a Mach number of 0.8 the spoiler-slot-deflector gives a large increase in rolling effectiveness, which demonstrates the advantage of low wing twist associated with spoiler-type controls.

Jet Controls

Another type of control that has characteristics very similar to those of the spoiler type of control is the jet control, which can use either free-stream air or compressed air to obtain control. Figure 6 shows some results for a model of the D-558-II airplane equipped with both flap-type and jet ailerons that were obtained in the Langley high-speed 7- by 10-foot tunnel. The variation of rolling-moment coefficient C_l with angle of attack is shown for both the conventional ailerons and the jet controls at a Mach number of 0.90. The jet control in this case picks up free-stream air in the wing tip inlet, directs it through a duct in the wing, and ejects it normal to the wing trailing edge through a series of holes in the thickened trailing edge. The values of C_l are for the condition in which air is blowing up out of one wing and down out of the other. The jet control at this Mach number was about as effective as the regular ailerons deflected their full amount, $\pm 15^{\circ}$.

The results of some preliminary studies with compressed air are shown in figure 7. In this case compressed air was ejected through the holes located on the 65-percent-chord line. On the left-hand side the rolling-moment coefficient C_l is plotted as a function of the momentum coefficient C_{μ} for the 35° swept wing at an angle of attack of 4° and a Mach number of 0.9. The rolling-moment coefficient varies linearly with momentum coefficient, and a comparison with the computed jet reaction (dashed line) reveals that most of the control power is obtained from changes in the circulation around the wing. On the right-hand side of figure 7, the rolling effectiveness $pb/2V$ is plotted as a function of the weight rate of flow W for an airplane with this plan form and a wing area of 335 square feet, flying at a Mach number of 0.9 and at an altitude of 10,000 feet. These values are based on the air being taken from the tail pipe, and thus on a jet velocity of about 2,000 feet per second. Too little is known about these controls to say how much the amount of air required might be reduced by configuration changes, but a reduction of about 25 percent could be expected if the jets were moved to the trailing edge, the location used in the D-558-II studies of figure 6. If the air for this type of control is taken from the tail pipe, the parameter C_{μ} is essentially the loss in thrust coefficient of the airplane; another way of looking at it is that the value of C_{μ} is the approximate increase in drag coefficient associated with control deflection.

Three different types of jet controls using free-stream air have been studied by the Langley Pilotless Aircraft Research Division by means of rocket models at high subsonic and low supersonic speeds. Figure 8 compares the rolling performance $pb/2V$ over the Mach number

range for the three jet controls on an 80° delta-wing configuration. The top configuration picks up air at the wing tip and ejects it normal to the wing surface through holes along the wing trailing edge; and the next one also picks up the air at the tip, but ejects it along the wing surface toward the wing root. These two types have about the same effectiveness at supersonic speeds. The other configuration is the least effective of the three; it picks up the air at the wing root and ejects it along the wing surface toward the wing tip. One current missile requires a value of $pb/2V$ of about 0.02 for roll stabilization throughout the speed range. Thus, any of these configurations would be satisfactory roll-stabilization devices and, due to their nature, could have low operating forces.

Reaction Controls

Any aircraft can have regions of flight (at very low speeds or at very high altitudes) in which the dynamic pressure is so low that conventional control surfaces would have to be very large to provide adequate control. In these regions reaction controls can be used. Figure 9 shows four different reaction controls that have been studied by the NACA. At the top of the figure are two configurations studied at the Lewis Flight Propulsion Laboratory at a Mach number of about 1.6. Hot air was used as the jet exhaust, and the configurations are typical of those that might be used on jet engines. The one on the left obtains its control by deflecting the nozzle to turn the jet exhaust, and the one on the right turns the jet exhaust by deflecting a vane that extends across the jet. At the bottom of the figure are two configurations tested statically with rocket motors by the Langley Pilotless Aircraft Research Division. They represent devices that might be used in a supersonic jet exhaust. The one on the left turns the jet by deflecting a paddle into one side of the jet, and the one on the right turns the jet by deflecting a spoiler into the jet stream. These configurations are only four of the many that have been studied by the NACA and other organizations. They are shown here only to give some idea of the thrust loss that may be associated with this type of control.

Figure 10 shows the thrust loss associated with the lateral force for the four controls of figure 9. In order to generalize the data, both the thrust loss and the lateral force were divided by the basic thrust. Of these configurations, the swiveled nozzle gives the most lateral force for the least thrust. In fact, it is equal to 1 minus the cosine of the deflection angle, the minimum possible loss. All the other devices show more thrust loss for a given lateral force, and the immersed vane has the undesirable feature of causing about a 2 percent loss when in the neutral position. Neither the spoiler nor the paddle appears to be able to furnish the lateral force that can be obtained with either the swiveled nozzle or the immersed vane.

When controls of this type are used on rocket-powered missiles, it is often desirable to maintain control after rocket burnout. One scheme for doing this without adding another control is shown in figure 11, where the trim normal-force coefficient $C_{N_{TRIM}}$ is shown as a function of Mach number for a cruciform delta-wing missile tested by the Langley Pilotless Aircraft Research Division. For control, a paddle-type reaction control was used, but instead of deflecting just one paddle as in figure 9, both the upper and lower paddles were deflected together. The upper vane deflects the jet in the power-on condition and the bottom vane acts as a body flap in the power-off condition. Although the power-off control was not as powerful as the power-on control, trim normal-force coefficients of 1/2 to 2/3 the power-on values could be obtained with power off with this control.

CONCLUDING REMARKS

The results indicate that, in addition to flaps and spoilers, air can now be used in the form of jet controls or reaction controls as alternate means of controlling the aircraft.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 2, 1955.

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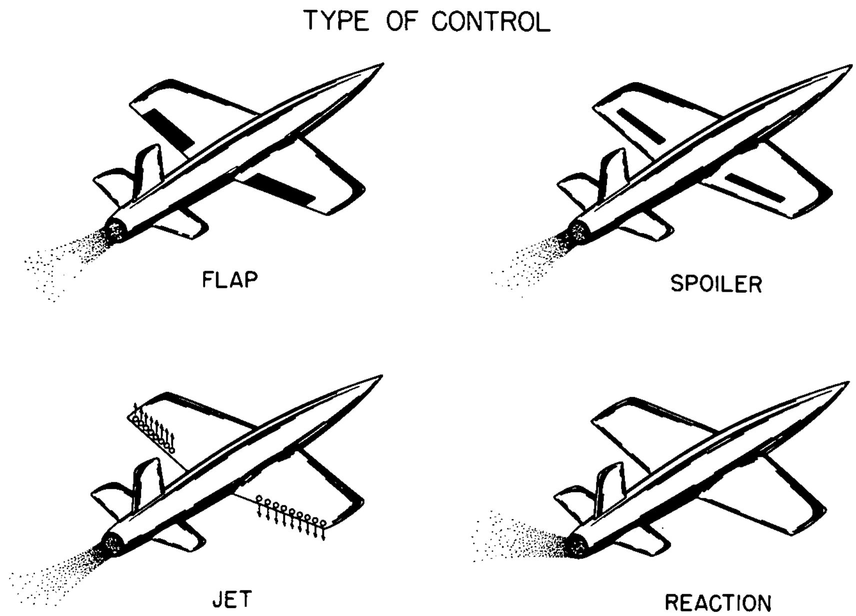

Figure 1

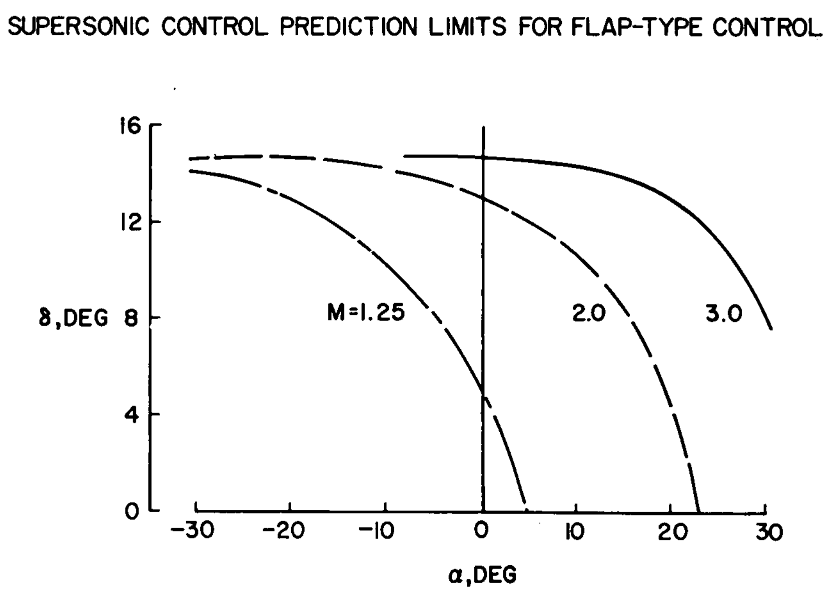

Figure 2

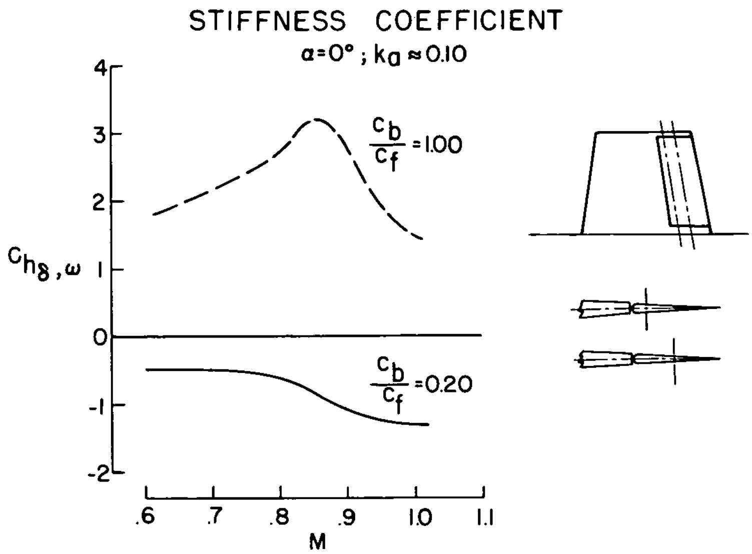

Figure 3

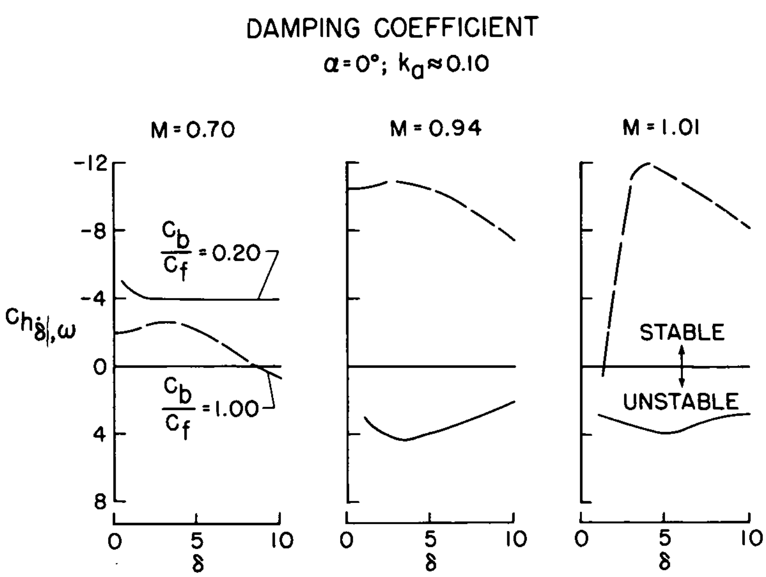

Figure 4

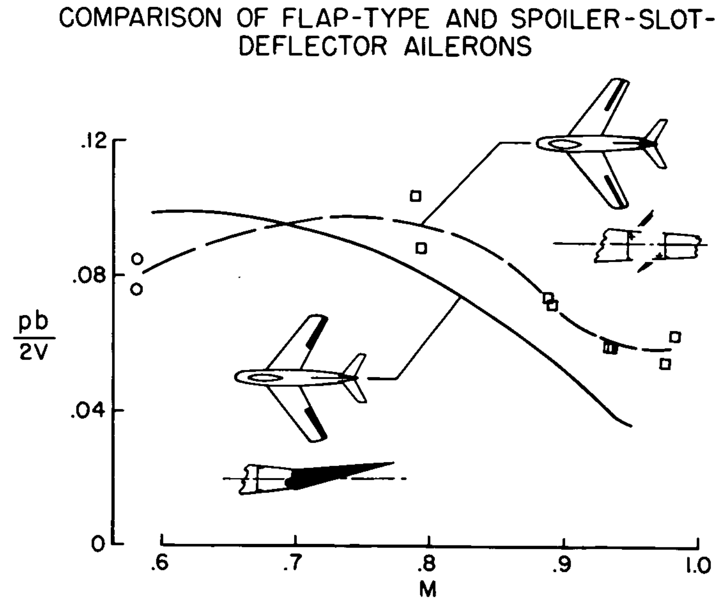

Figure 5

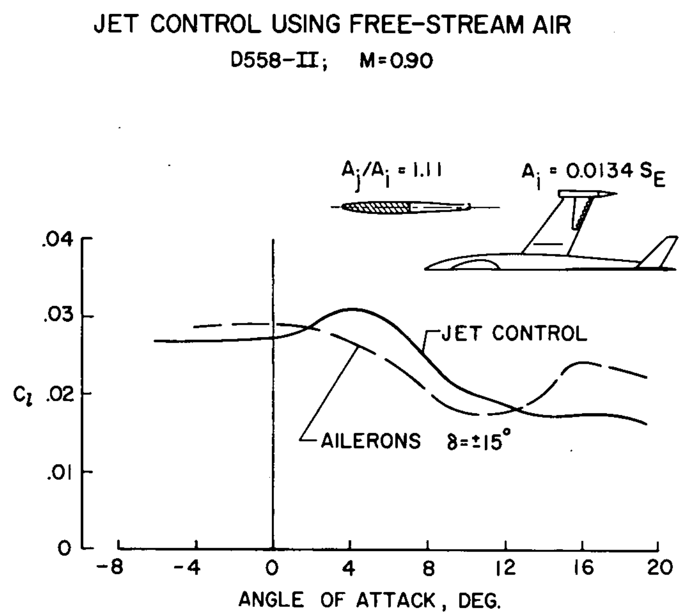

Figure 6

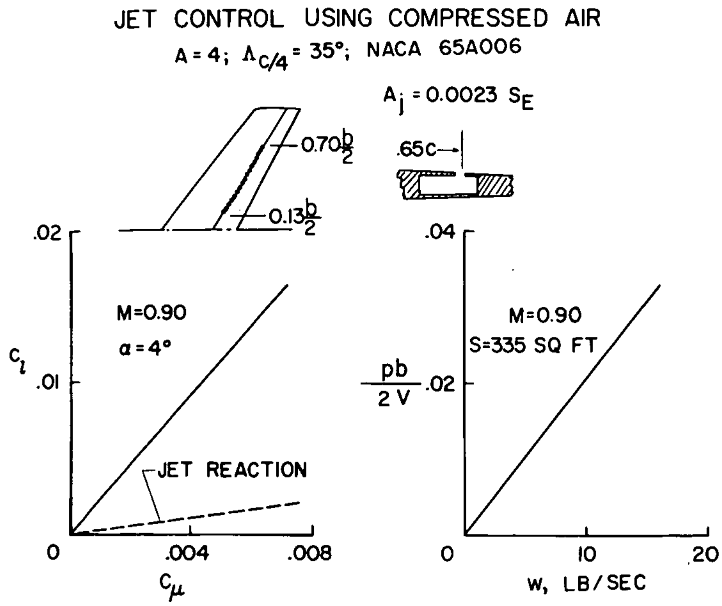

Figure 7

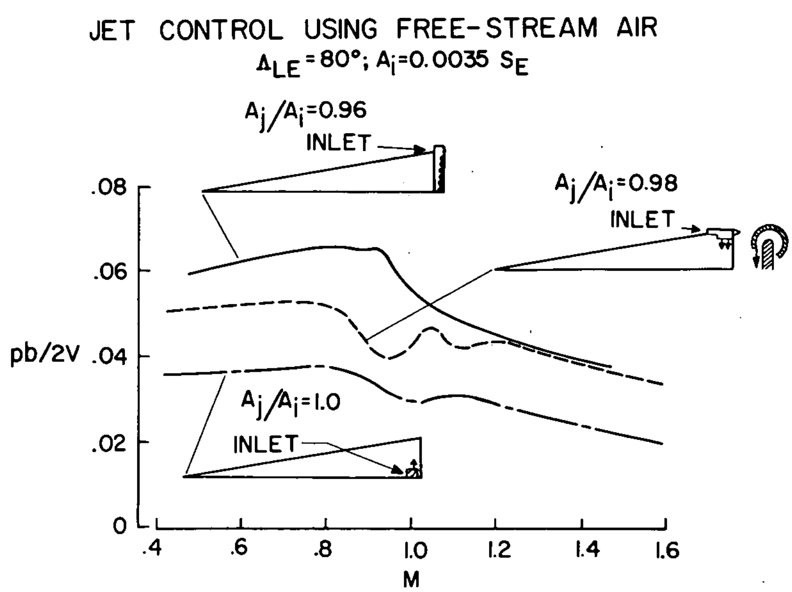

Figure 8

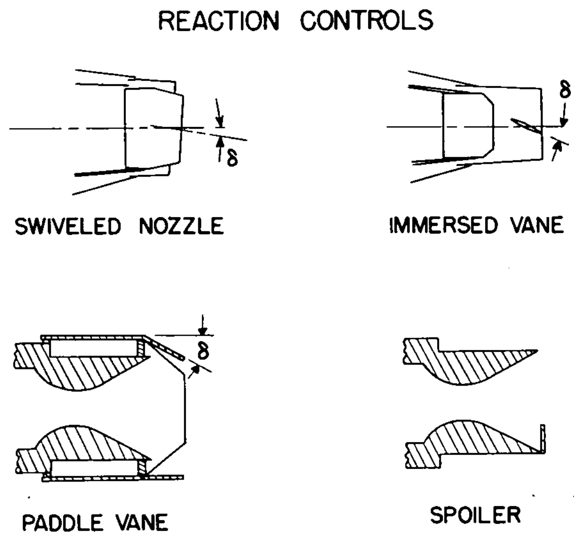

Figure 9

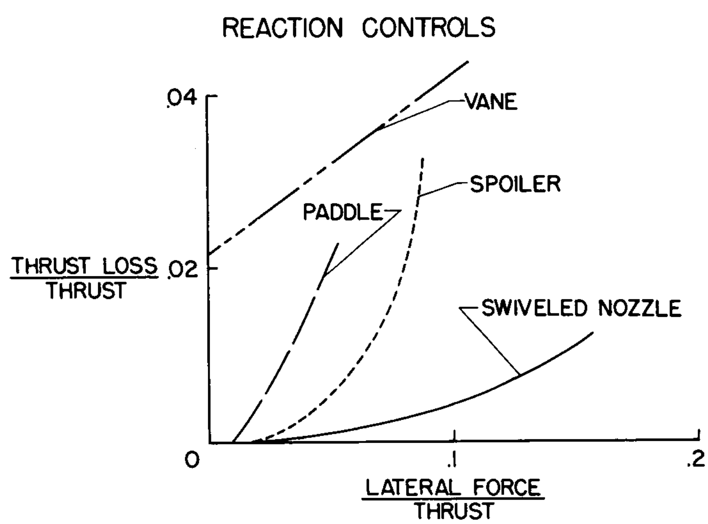

Figure 10

PADDLE VANE-REACTION CONTROL

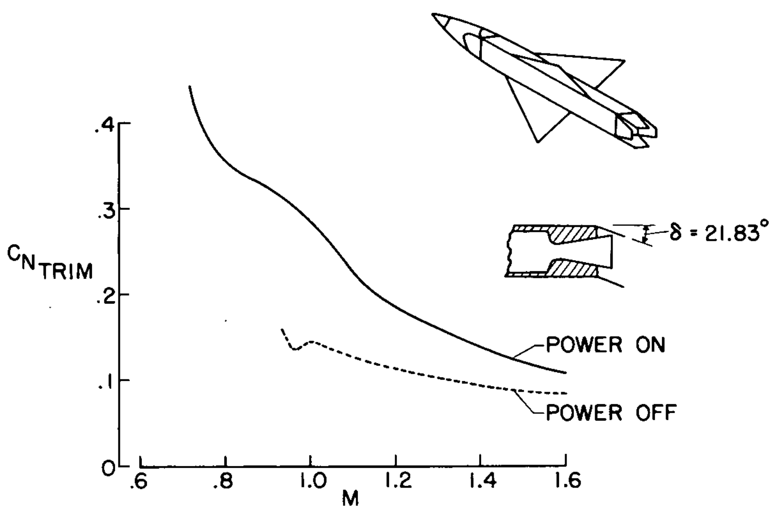

Figure 11